

AperTO - Archivio Istituzionale Open Access dell'Università di Torino

Effect of crop residue incorporation on soil organic carbon and greenhouse gas emissions in European agricultural soils

This is the author's manuscript

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/158067> since 2016-07-04T15:16:43Z

Published version:

DOI:10.1111/sum.12151

Terms of use:

Open Access

Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)



UNIVERSITÀ DEGLI STUDI DI TORINO

This is the accepted version of the following article: 22. Lehtinen, T., Schlatter, N., Baumgarten, A., Bechini, L., Krüger, J., Grignani, C., Zavattaro, L., Costamagna, C., Spiegel, H., 2014. Effect of crop residue incorporation on soil organic carbon and greenhouse gas emissions in European agricultural soils. *Soil Use Manage* 30, 524–538. doi:10.1111/sum.12151,

which has been published in final form at

<http://onlinelibrary.wiley.com/doi/10.1111/sum.12151/abstract>

<http://onlinelibrary.wiley.com/doi/10.1111/sum.12151/pdf>

Effect of crop residue incorporation on soil organic carbon (SOC) and greenhouse gas (GHG) emissions in European agricultural soils

Taru Lehtinen^{1,2,3}, Norman Schlatter^{1*}, Andreas Baumgarten¹, Luca Bechini⁴, Janine Krüger⁵, Carlo Grignani⁶, Laura Zavattaro⁶, Chiara Costamagna⁶, Heide Spiegel¹

¹Institute for Sustainable Plant Production, Department for Soil Health and Plant Nutrition, Austrian Agency for Health and Food Safety (AGES), Spargelfeldstraße 191, AT-1220 Vienna, Austria

²Institute of Soil Research, Department of Forest and Soil Sciences, University of Natural Resources and Life Sciences, BOKU, Peter Jordan Straße 82a, AT-1190 Vienna, Austria

³Faculty of Life and Environmental Sciences, University of Iceland, Sturlugata 7, IS-101 Reykjavik, Iceland

⁴Department of Agricultural and Environmental Sciences, Università degli Studi di Milano, Via G. Celoria 2, IT-20133 Milan, Italy

⁵Leibniz-Institute of Vegetable and Ornamental Crops, Theodor-Echtermeyer-Weg 1, DE-14979 Grossbeeren, Germany

⁶Department of Agricultural, Forest and Food Sciences (DISAFA), Università degli Studi di Torino, Via Leonardo Da Vinci 44, IT-10095 Grugliasco, Italy

Running title: Effect of crop residues on soil

*Corresponding author:

Norman Schlatter

norman.schlatter@ages.at

Tel: +43 (0)50 555 34116

Fax: +43 (0)50 555 34101

Spargelfeldstraße 191

AT-1220 Vienna

Austria

Abstract

Soil organic matter (SOM) improves soil physicochemical and biological properties, and the sequestration of SOM may mitigate climate change. Soil organic carbon (SOC) often decreases in intensive cropping systems. Incorporation of crop residues (CR) may be a sustainable management practice to maintain the SOC levels and to increase soil fertility. This study quantifies the effects of CR incorporation on SOC and greenhouse gas (GHG) emissions (CO_2 and N_2O) in Europe using data from long-term experiments. Response ratios (RRs) for SOC and GHG emissions were calculated between CR incorporation and removal. The influences of environmental zones (ENZs), clay content and experiment duration on the RRs were investigated. We also studied how RRs of SOC and crop yields were correlated. A total of 718 RRs were derived from 39 publications. The SOC increased by 7 % following CR incorporation. In contrast, in a subsample of cases, CO_2 emissions were six times and N_2O emissions 12 times higher following CR incorporation. The ENZ had no significant influence on RRs. For SOC concentration, soils with a clay content >35 % showed 8 % higher RRs compared to soils with clay contents between 18 and 35 %. As the experiment progressed, RR for SOC concentration and stock increased. For N_2O emissions, RR was significantly higher in experiments with a duration <5 years compared to 11-20 years. No significant correlations were found between RR for SOC concentration and yields, but differences between sites and study durations were detected. We suggest a win-win scenario to be crop residue incorporation for a long duration in a continental climate, whereas the worst-case scenario involves crop residue incorporation over the short term in the Mediterranean, especially with vegetative material. We conclude that CR incorporation is important for maintaining SOC, but its influence on GHG emissions should be taken into account as well.

Keywords: carbon dioxide (CO_2), nitrous oxide (N_2O), soil organic carbon, response ratio, crop residue management, climate change

1. Introduction

Soil organic matter improves soil physical (e.g. increased aggregate stability), chemical (e.g. cation exchange capacity) and biological (e.g. biodiversity, earthworms) properties, and it mitigates climate change by sequestering carbon in soils (Lal, 2013). Currently, as much as 25-75 % of the SOC in the world's agricultural soils may have been lost due to intensive agricultural practices (Lal, 2013), and about 45 % of European soils exhibit low organic matter contents (European Commission, 2006). The decline of OM is one of the major threats to soils described by the European Commission (European Commission, 2006).

Globally, approximately four billion tons of crop residues are produced (Chen et al., 2013). Removal of crop residues has a negative effect on SOC, but an estimated 25-50 % of crop residues could be harvested without threatening soil functions (Blanco-Canqui, 2013). Harvesting crop residues may be beneficial for farmers because residues can be used as livestock bedding, sold or thermally utilized. Harvesting residues also fits reduced or no-tillage farming operations because the soil will be less disturbed due to no ploughing of crop residues into the soil. Incorporation of crop residues may be a sustainable and cost-effective management practice to maintain the ecosystem services provided by soils, the SOC levels and to increase soil fertility in European agricultural soils (Perucci et al., 1997; Powlson et al., 2008). In particular, Mediterranean soils with low SOC concentrations (Aguilera et al., 2013), and areas where stockless croplands predominate (Kismányoky and Tóth, 2010; Spiegel et al., 2010b), could benefit from this management practice. Nonetheless, crop residue incorporation increases the SOC concentrations and stocks less than does farmyard manure (Cvetkov et al., 2010) or slurry (Triberti et al., 2008). For GHG emissions, both positive and negative effects have been observed following crop residue incorporation (e.g. Abalos et al., 2013). Emissions of CO₂ indicate heterotrophic microbial activity and particularly mineralization (Baggs et al., 2003), whereas N₂O emissions indicate both nitrification and denitrification processes (Chen et al., 2013). The lack of studies focusing on both SOC and GHG emissions (Ingram and Ferdandes, 2001) calls for an analysis of European results.

The response of soil properties to management practices may depend on various factors such as soil temperature and soil moisture content, soil clay content (Körschens, 2006; Chen et al., 2013) or duration of the experiment (Smith et al., 2012; Chen et al., 2013). Metzger et al. (2005) presented a stratification of environmental zones (ENZs) in Europe, which is based on climate, geology and soils, geomorphology, vegetation and fauna. It can be used to compare the response of soil to management practices across Europe (Jongman et al., 2006). In their meta-analysis, Chen et al. (2013) showed that the clay content was a good predictor for N₂O emissions following crop residue incorporation. Especially in the case of soil processes, the experiment duration improves the accuracy of data. Accordingly, long-term experiments are very important when assessing the impact of a management practice on soil (Körschens, 2006). Effects of crop residue incorporation on SOC and GHG emissions have been studied across the world (Chen et al., 2013, Liu et al., 2014), but the results differ due to the wide range of systems inherent in a global coverage. Studies with both SOC and GHG emissions are still missing. An analysis of European long-term experiments (LTEs) helps integrate current knowledge in Europe and provides guidance for policy development.

This study was designed to quantify the effects of crop residue incorporation on SOC and GHG emissions in varying environmental zones in Europe, using the published results of LTEs. Specifically, we addressed the following questions:

- i) Are environmental zones an important factor for analysing the effects of crop residue incorporation on SOC concentration and stock, as well as on GHG emissions (CO₂, N₂O)?
- ii) Does the effect of crop residue incorporation change with a change in clay content?
- iii) Does the duration of the experiment influence the response ratios of SOC and GHG emissions following crop residue incorporation?
- iv) Do the experimental setup and crop residue type affect the RR of GHG emission following crop residue incorporation?
- v) Are RRs for SOC concentrations and yields correlated?

SOC stocks were analysed separately in order to confirm the results emerging from SOC concentrations. We hypothesised that the response ratios of SOC increase the most in the Nemoral ENZ due to low temperatures, particularly in high clay content soils due to interactions between SOC and clay minerals, and furthermore increase with time. The response ratios of GHG emissions were expected to be lowest in the Nemoral ENZ, and to decrease with time. We expected the response ratios of GHG emissions to be higher in laboratory versus field experiments due to more favourable conditions for the microorganisms, such as optimal soil water content. The RR of GHG emissions were expected to be higher with incorporation of low-C/N-ratio crop residues (hereafter referred to as “vegetative material” such as sugar beet, potato or leafy greens compared to high-C/N-ratio crop residues, hereafter referred to as “cereal” such as barley, wheat or maize residue incorporation). Further, we expected to observe a positive correlation between yields and SOC concentrations, as higher yields would result in more residues and greater accumulation of SOC.

2. Materials and methods

2.1 Data sources

A detailed literature review was conducted concerning scientific publications that had reported on long-term agricultural experiments in Europe. This yielded a total of 718 response ratios from 39 publications (Table 1), 50 experiments in 15 countries. An online database was created, which included 46 field experiments and four laboratory experiments that covered 10 European Environmental Zones (ENZs), as defined by Metzger et al. (2005), and four aggregated ENZs (Figure 1, Table 2). Most of the data were published in peer-reviewed scientific journals, while a smaller fraction were published in national technical journals and conference proceedings. The publications report on measurements of SOC concentration, SOC stock, and CO₂ and N₂O emissions from pairwise comparisons of crop residue incorporation and crop residue removal management practices. The minimum requirements for data being included were that the

studies had i) replicates and ii) paired treatments that compared crop residue incorporation and removal. Further, we only included experiments in which crop residue incorporation and removal were investigated under the same climatic and soil conditions, as well as with similar fertilization levels. For CO₂ and N₂O emissions, data from long-term experiments were scarce. For these variables, shorter experiment durations and laboratory experiments were included in the database. For this analysis, mostly publications reporting data in tables, which could be directly transferred into the database, were used. Data given in figures were extracted using the program WebPlotDigitizer (Rohatgi, 2013).

2.2 Data preparation

If SOC concentrations but no bulk density (BD) or SOC stock data were reported, the latter two properties were estimated according to the formulas mentioned below to increase the number of studies. For 26 experiments in which BD was not available, it was calculated according to Ruehlmann and Körschens (2009):

$$BD = (2.684 - 140.934 * 0.008) * \text{EXP}(-0.008 * \text{SOC})$$

where BD is the standardised bulk density (Mg m⁻³), 2.684 is the mean density of mineral soil particles (Mg m⁻³) as estimated by Rühlmann et al. (2006), 140.934 is the fitted coefficient, 0.008 is the coefficient for arable soils, and SOC is the concentration of soil organic carbon (g kg⁻¹).

SOC stock (Mg C ha⁻¹) in the corresponding soil layer was calculated as:

$$\text{SOC stock} = \text{SOC} * D * \text{BD} * 10$$

where SOC is the concentration of soil organic carbon (g kg⁻¹), D is the thickness of the soil layer (m), and BD is the soil bulk density (Mg m⁻³).

For each pairwise comparison, a response ratio (RR) was calculated as:

$$RR = \text{property}_I / \text{property}_R$$

where $property_I$ is the SOC concentration, SOC stock, CO₂ emission, or N₂O emission in crop residue incorporation management practice, and $property_R$ is the SOC concentration, SOC stock, CO₂ emission, or N₂O emission in crop residue removal management practice. RR >1 was assumed to be an improvement in SOC concentrations and stocks, whereas RR >1 for CO₂ and N₂O emissions was assumed to be an undesirable increase in GHG emissions.

2.3 Data aggregation

In some cases it was possible to derive more than one comparison from an experiment, e.g. when they report on multiple years or multiple contrasting managements. For stepwise linear multiple regressions and one-way analyses of variance (ANOVA), we used a single average of the response ratios for each experiment to aggregate multiple within-experiment response ratios prior to a between-study analysis (Lajeunesse, 2011). These averages were weighted based on the number of response ratios (sample size) from the experiments, because in many publications the standard deviation (SD) and number of samples (n) were missing.

2.4 Data analysis

The statistical analyses were performed using the IBM SPSS Statistics 20 software package for Mac. The normality of data was checked with Shapiro-Wilk's test. All data on SOC concentration, SOC stock and GHG emissions (CO₂ and N₂O) were not normally distributed, thus log-transformed before the statistical analyses to obtain homogeneity of variances. A stepwise linear multiple regression was used to identify the significant continuous variables (temperature, precipitation, clay content, duration of the experiment were tested) on RR of SOC concentration, SOC stock, and GHG emissions (Table 3). To strengthen our analyses, the effect of the variables ENZ, clay content, and experiment duration (as aggregated into specific levels in Table 2) were investigated with ANOVA with Tukey's significance test ($p < 0.05$) as a Post Hoc test. Correlations between variables were presented in Pearson correlation coefficients.

3. Results

Crop residue incorporation increased the SOC concentration and SOC on average by 7% (Figure 1), whereas CO₂ emissions were increased almost six fold and N₂O emissions more than twelve fold on average (n = 84 and 97, respectively). Multiple regressions revealed that experiment duration had highest effect on SOC concentration, explaining 14% of the variation (Table 3). For SOC stock, both clay content and experiment duration affected the response ratio and explained 22% of the variation (Table 3). 98% of the variation in RR of CO₂ emissions was explained by clay content alone, whereas approximately 75% of the variation in RR of N₂O emissions was explained by clay content and temperature (Table 3).

3.1 Effect of environmental zone

The effect of the aggregated ENZ on the response ratio of SOC concentration was not significant (Figure 2A). In contrast, the response ratio of the SOC stock was 4% lower in the Mediterranean versus the Continental Zone (Figure 2B). For GHG emissions, data were retrieved only for Atlantic and Mediterranean ENZs (Table 4). The RR for CO₂ for the Atlantic Zone was significantly higher than for the Mediterranean. For N₂O emissions, RR was higher for the Atlantic Zone compared to Mediterranean, although not significantly due to the high variability normally associated with this measurement.

3.2 Effect of clay content

Among different clay contents, a content >35 % was found to be associated with significantly higher response ratios for SOC concentration compared to contents between 18 and 35 % (Figure 2C). The same was observed for SOC stocks (Figure 2D). Data for GHG emissions were retrieved only for the clay contents <18% and 18-35 % (Table 4). The RR for CO₂ for <18 % clay content was seven fold higher compared to 18-35 % clay content. For N₂O, the effect of clay was similar as for CO₂, being twice as high in soils with clay contents <18 % compared to 18-35 %. This difference, however, was not significant.

3.3 Effect of experiment duration

As the duration of the experiment rose, RR for SOC concentration increased (Figure 2E). The RR was statistically higher for experiments lasting >20 years compared to the other duration groups. Also, the RR for SOC stock was dependent on experiment duration (Figure 2F), being significantly lower in experiments <5 years compared to the duration groups 11-20 and >20 years. For CO₂ (Table 4), no distinction between duration groups could be detected because all the RRs were in the <5 years group. For N₂O, RR was significantly higher in experiments lasting <5 years compared to the 11-20 years duration. Note, however, that there was only one experiment in the 11-20 years duration group.

3.4 Effect of experiment and crop residue type on RR for GHG emissions

We observed higher response ratios for CO₂ and N₂O emissions in laboratory experiments compared to field experiments (Table 4), except for N₂O emissions when cereal crop residues were incorporated. The RR was higher in vegetative material crop residue incorporation experiments compared to cereal crop residue incorporation experiments (Table 4). In field experiments for N₂O emissions, however, the effect was opposite. This was a result of lower RR in vegetative material crop residue incorporation experiments compared to cereal crop residues in the Mediterranean environmental zone with 18-35 % clay content and less than five years experiment duration (Table 4).

3.5 Correlation between SOC concentration and crop yields

The mean RR for yield was 1.06 ± 0.15 (n=71). This means that crop residue incorporation resulted in an average 6 % yield increase compared to crop residue removal. We expected to observe an increase in SOC together with an increase in yield due to a positive feedback between crop residue incorporation, nutrient availability, crop nutrient uptake rate, and finally crop growth rate. From another perspective, higher crop yield means higher crop residue production, followed by higher SOC when these crop residues are incorporated. Unexpectedly, however, no significant correlation ($r=0.02$, $p>0.05$) was found between the RR of SOC concentration and the RR of yield. Differences between the studied sites (Figure 3A), ENZs (Figure 3B), and experiment

234 durations were found (Figure 3D). No differences were detected between different clay content
235 groups (Figure 3C). No effect of crop type was recorded, but yield data were available only for
236 the crops wheat, barley and maize. The sites Kesthely, Grossbeeren 2, and Ultuna had the highest
237 RRs in both SOC concentration and yield, whereas Almacelles 1 and 2 were among the sites with
238 lowest RRs. As the experiment duration increased, the RRs increased with the exception of
239 Foggia 1 and Foggia 2, where RR for yields was below one even when the experiment lasted
240 more than twenty years.

241 4. Discussion

242 The results of this analysis demonstrate an increase in RR of SOC concentration and stock
243 following crop residue incorporation (Figure 2) representing an additional annual C input. The
244 same has been demonstrated in previous meta-analyses for organic inputs (Lemke et al., 2010;
245 Powlson et al., 2012), e.g. in organic farming (Gattinger et al., 2012; Aguilera et al., 2013).
246 Incorporation of crop residues is one of the few methods applied by farmers to maintain SOC
247 and to sustain soil functions (Powlson et al., 2008). This makes it a very important management
248 tool. Even a small increase in SOC can improve soil physicochemical and biological properties
249 and ecosystem services such as nutrient cycling and possible increases in yields (Loveland and
250 Webb, 2003; Bhogal et al., 2009; Blanco-Canqui, 2013).

251 The overall data for CO₂ and N₂O emissions were collected from both field and laboratory
252 experiments as well as from experiments that incorporated cereals and vegetative materials.
253 Thus, the standard deviation was high for these indicators, possibly due to spatial heterogeneity
254 driven by variability in soil characteristics. With crop residue incorporation, CO₂ emissions will
255 increase compared to crop residue removal due to more easily available C that enhances
256 microbial activity (Meijide et al., 2010). In contrast, if crop residues are removed, they will be
257 decomposed elsewhere, used as bedding and incorporated into farmyard manure or burned,
258 releasing approximately the same amount of CO₂ (Blanco-Canqui, 2013). Thus, crop residue
259 incorporation is not primarily a way to decrease CO₂ emissions and may not be beneficial for all

soil ecosystem services such as carbon sequestration. In order to close the knowledge gap and to give better-informed recommendations to farmers, further field-scale research focusing on in situ carbon balance is required.

In the case of N_2O , emissions from crop residue incorporation are up to twelve times higher compared to crop residue removal. Emissions of N_2O occur both during the nitrification process and as a result of anaerobic denitrification. The latter process requires the presence of microbes capable of using nitrates. The increase of the RR for N_2O following crop residue incorporation in a study by Baggs et al. (2003) was explained by mineral N fertilization and an increased denitrification capacity stimulated by the added substrate. In our analysis, no distinct relationships were found with mineral N fertilisation ($r=0.08$, $p>0.05$), most likely due to the limited number of data. The soil respiration process may create anaerobic microsites in the soil and thereby increase N_2O emissions through denitrification (Garcia-Ruiz and Baggs, 2007; Abalos et al., 2013). Nonetheless, the N_2O emissions caused by the crop residues should be put in relation to the fact that not all removed crop residues are decomposed or burned with no N_2O emissions.

4.1 Effect of environmental zone

The aggregated ENZ proved not to be a determining factor when RRs for SOC concentration, SOC stock, CO_2 and N_2O emissions were studied (Figure 2, Table 4). This is in contrast with concepts in which climate is directly and indirectly linked with carbon concentrations in soils (e.g. Ingram & Fernandes, 2001). One explanation may be that the aggregated ENZs in our study were too broad categories to capture the differences between different climates. ENZ are assigned based on several factors beyond climate, such as geomorphology, vegetation and fauna (Metzger et al., 2005). Given the large heterogeneity in these environmental factors across the experimental sites in this study, probably more data would have been required to detect significant differences between ENZs. In previous studies, temperature has been found to be one of the

driving factors for both N₂O (Mutegei et al., 2010) and CO₂ emissions (Meijide et al., 2010). This was also supported by our multiple regressions, in the case of N₂O (Table 3).

4.2 Effect of clay content

Our results indicated higher RR for SOC concentration and stock with higher clay content (Figure 2C, D), probably because the clay fraction physically protects organic matter molecules from mineralization (Lal, 1997). SOM may be physically protected in the clay fraction of fine-textured soils by chemical bonds due to high surface activity (Six et al., 2000), thereby being inaccessible for microbial degradation (von Lützow et al., 2006). Nonetheless, the low clay content (<18 %) soils also showed a positive SOC response to management changes (Cvetkov and Tajnsek, 2009). This may be explained by SOC being accumulated as POM in the sand fraction of these soils, and not additionally in the clay fraction, as has been shown in tropical soils (Feller and Beare, 1997; Chivence et al., 2007). Furthermore, the initial SOC concentration of the soil may play a role in how much C is retained in the fine fraction (Poirier et al., 2013). The authors showed that low-SOC-concentration soils have a greater capacity to accumulate C in the fine fraction when high amounts of crop residues are added to the soil.

For GHG emissions the number of experiments and RRs was too small to allow a representative analysis of differences between clay content groups. Velthof et al. (2002) compared sandy and clay soils under laboratory conditions and found the N₂O emissions to be much lower in the latter than in the former. This is supported by our analysis of field data on cereal crop residue incorporation (Table 4), but more measurements would be necessary before generalisations could be made. Indications of lower RR of N₂O emission in lower-clay-content soils are in accordance with a recent meta-analysis that confirmed the influence of texture on N₂O emissions (Chen et al., 2013). Soil texture may influence the response to crop residue incorporation through O₂ availability in soil microsites and its influence on denitrification (Chen et al., 2013).

4.3 Effect of experiment duration

The observed higher response ratios for SOC concentration and stock for longer experiment durations (Figure 2) agree with previous studies (Körschens et al., 1998). The low clay-content (<18 %) soils showed a positive SOC response to management changes after ten years of management difference (Cvetkov and Tajnsek, 2009), but it may be that SOC saturation in soils with low clay content is reached faster than in high content (>35 %). As experiment duration increases, more interactions between clay minerals and SOC may take place (von Lützow et al., 2006); this is accompanied by a more marked accumulation of resistant crop residue C that is not mineralised (De Neve and Hofman, 2000), especially in soils without mechanical tillage (Six et al., 2000). Hence, the increase in SOC concentration has its limits and the accumulation rate becomes smaller when the soil system is close to a new equilibrium (Powlson et al., 2008).

For GHG emissions, the influence of the experiment duration was the opposite (Table 4), supporting a study by Chen et al. (2013). Those authors analysed experiment durations above and below 70 days and showed that the RR is initially higher, but as the duration increases, the RR of GHG emissions is also lower. Peak microbial activity when easily available organic inputs (crop residues) are added into the soil (Recous et al., 1995) may explain this response (Powlson et al., 2011).

4.4 Effect of experiment and crop residue type on RR for GHG emissions

The higher response ratios of N₂O emissions in vegetative material laboratory experiments compared to field experiments (Table 4) agree with a meta-analysis that studied N₂O emissions following crop residue incorporation (Chen et al., 2013). Those authors explained the difference by the smaller size and subsequent increase of surface area of the crop residues in the laboratory experiments compared to field-scale applications. This applies to laboratory experiments in our analysis (Velthof et al., 2002; Garcia-Ruiz & Baggs, 2007; Cayuela et al., 2013), compared to the field experiments (Baggs et al., 2003; Mutegi et al., 2010; Abalos et al., 2013; Sanz-Cobena et al., 2014). Moreover, under laboratory conditions moisture and

temperature are stable and optimised for microbial activity, thus promoting higher emissions compared to field experiments (Chen et al., 2013).

Previous studies show that N₂O emissions decrease at a higher C/N ratio of the residues (Alexander, 1977; Shan and Yan, 2013). This is in line with the observed higher RR of GHG emissions (Table 4) in vegetative material crop residue incorporation experiments compared to cereal crop residue incorporation experiments in our study. This may be explained by immobilisation of N with increasing C/N ratio of the crop residues (Abalos et al., 2013). The oxidation rate is higher immediately after the incorporation of vegetative material (versus cereal residues) due to quick decomposition, thus possibly promoting higher denitrification rates (Nicolardot et al., 2001; Rizhiya et al., 2011). Higher GHG emissions from low-C/N-ratio crop residue incorporation were observed in individual studies under field conditions in our analysis (e.g. Baggs et al., 2000; 2003). This can be explained by higher availability of N first for nitrification and then for denitrification when the C/N ratio of incorporated crop residue is low (Baggs et al., 2003). Garcia-Ruiz and Baggs (2007), however, stated that more knowledge on the interactions between organic and inorganic N sources and compounds released from the crop residues is required before drawing conclusions on how to reduce GHG emissions following crop residue incorporation.

One additional explanation for the RR of GHG emissions may be the cultivation technique, which affects the nutrient supply to microorganisms and the aeration (Baggs et al., 2003; Mutegi et al., 2010). However, soil tillage was not in the scope of this study. Another potential factor is N fertilisation, which increased GHG emissions in several studies (e.g. Garcia-Ruiz and Baggs, 2007; Meijide et al., 2010; Sanz-Cobena et al., 2014). Nevertheless, our analysis did not reveal any significant correlations between N₂O emissions and mineral N fertilisation. This may be due to limited data accessibility and differences in the set-up of the experiments we investigated. The differences observed between ENZs, clay content groups and experiment durations within experiment types and crop residue types most likely reflected differences between experiments

and not between the categories. More data from long-term field experiments are required to enable a study of such relationships.

4.5 Correlations between crop yields and SOC concentrations

The slight positive influence of crop residue incorporation on crop yield (Figure 3A) contradicts previous studies reporting yield decreases (Swan et al. 1994; Nicholson et al., 1997), but agrees with Wilhelm et al. (2004). The positive influence of crop residue incorporation may be explained by the increase in SOC and the experiment duration (Figure 3A, D). Crop residues act as a continuous source of soil nutrients and soil organic matter (Liu et al., 2014), which improves soil functioning (Bhogal et al., 2009) and thereby yields. Thus, a positive feedback, initiated by incorporation of crop residues, occurs. In the case of the Foggia experiment (Figure 3A), the incorporation of crop residues lowered yield because of the poor mineralisation and strong N immobilisation due to arid climate and the low soil N status (Maiorana, 1998). Mineral N fertilization did not increase yields at Almacelles even though SOC concentrations were sufficient, possibly due to the short duration of the experiment and the arid climate (Biau et al., 2013).

4.6 Possible improvements of the data set for future analyses

Long-term experiments with data on SOC concentrations, stocks and GHG emissions from the same experiment are lacking in our dataset. To reach sustainable agricultural management with a positive soil carbon budget, both SOC and GHG emissions should be taken into account (Ingram & Ferdandes, 2001; Lal, 2013). This calls for long-term field experiments to study these interactions and possible trade-offs between management practices (Körschens, 2006). The present study was based on measurements from the topsoil (<30 cm), in the future it would be important to investigate SOC concentrations and stocks also in the deeper soil layers (Aguilera et al., 2013; Lal, 2013).

5. Conclusions

This analysis indicates that the impacts of crop residue incorporation on SOC concentration and stock are positive, but the CO₂ and N₂O emissions are increased. Even a small decrease in SOC may have detrimental effects on other soil properties such as aggregate stability. Thus, maintaining or even increasing SOC levels is crucial for agricultural soils. We show that long-term crop residue incorporation may increase crop yields. A win-win scenario between yield and SOC is crop residue incorporation over the longer term (>20 years) in a continental climate. The worst-case scenario would occur with short-term crop residue incorporation, especially with vegetative material, in a Mediterranean setting. Data availability from field experiments on GHG emissions is still scarce, and the data do not allow for selection of win-win and worst-case scenarios for these parameters. Thus, more long-term field studies are needed to better assess the CO₂ and N₂O emissions following crop residue incorporation, specifically from the same studies in which SOC is measured. We conclude that crop residue incorporation is an important management practice to maintain SOC concentrations and stocks and to sustain soil functioning, but that its influence on GHG emissions should be considered. GHG emissions should be measured in on-going long-term field experiments to more accurately calculate trade-offs such as in situ SOC and GHG balances following crop residue management in agricultural systems.

Acknowledgements

We thank the authors of the 50 experiments whose extensive field and laboratory work enabled us to conduct our analysis. This study was part of the European CATCH-C project that is funded within the 7th Framework Programme for Research, Technological Development and Demonstration, Theme 2 – Biotechnologies, Agriculture & Food (Grant Agreement N° 289782). Taru Lehtinen is thankful for the FEMech programme grant from the Federal Ministry for Transport, Innovation and Technology (BMVIT), Austria, to carry out this study. Jo Reilly and Michael Stachowitsch are acknowledged for English proofreading.

References

- Abalos, D., Sanz-Cobena, A., Garcia-Torres, L., van Groenigen, J.W. & Vallejo, A. 2013. Role of maize stover incorporation on nitrogen oxide emissions in a non-irrigated Mediterranean barley field. *Plant and Soil*, **364**, 357-371.
- Aguilera, E., Lassaletta, L., Gattinger, A. & Gimeno, B.S. 2013. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. *Agriculture, Ecosystems and Environment*, **168**, 25-36.
- Albert, E. & Grunert, M. 2013. Wirkung einer langjährig differenzierten mineralisch-organischen Düngung auf Ertrag, Humusgehalt, N-Bilanz und Nährstoffgehalte des Bodens. *Archives of Agronomy and Soil Science*, **59**, 1073-1098.
- Alexander, M. 1977. Mineralization and immobilization of nitrogen, In: Introduction to soil microbiology, 2nd edition (ed Alexander, M.). Wiley, New York, USA, pp. 136-247.
- Baggs, E.M., Stevenson, M., Pihlatie, M., Regar, A., Cook, H. & Cadisch, G. 2003. Nitrous oxide emissions following application of residues and fertiliser under zero and conventional tillage. *Plant and Soil*, **254**, 361-370.
- Baggs, E.M., Rees, R.M., Smith, K.A. & Vinten, A.J.A. 2000. Nitrous oxide emission from soils after incorporating crop residues. *Soil Use and Management*, **16**, 82-87.
- Ball, B.C., Bickerton, D.C. & Robertson, E.A.G. 1990. Straw incorporation and tillage for winter barley: Soil structural effects. *Soil and Tillage Research*, **15**, 309-327.
- Bertora, C., Zavattaro, L., Sacco, D., Monaco, S. & Grignani, C. 2009. Soil organic matter dynamics and losses in manured maize-based forage systems. *European Journal of Agronomy*, **30**, 177-186.
- Bhagal, A., Nicholson, F.A., & Chambers, B.J. 2009. Organic carbon additions: effects on soil bio-physical and physico-chemical properties. *European Journal of Soil Science*, **60**, 276-286.

434 Bianchi, A.A., Guiducci, M. & Bonciarelli, U. 1994. Effect of crop rotation and nitrogen fertilization
 435 on PAR absorption and radiation use efficiency of winter bread wheat. *Proceedings to the*
 436 *Third congress of the European Society for Agronomy*, pp. 70-71.

437 Biau, A., Santiveri, F. & Lloveras, J. 2013. Stover Management and Nitrogen Fertilization Effects
 438 on Corn Production. *Agronomy Journal*, **105**, 1264-1270.

439 Blanco-Canqui, H. 2013. Crop Residue Removal for Bioenergy Reduces Soil Carbon Pools: How
 440 Can We Offset Carbon Losses? *Bioenergy Research*, **6**, 358-371.

441 Börjesson, G., Menichetti, L., Kirchmann, H. & Kätterer, T. 2012. Soil microbial community
 442 structure affected by 53 years of nitrogen fertilisation and different organic amendments.
 443 *Biology and Fertility of Soils*, **48**, 245-257.

444 Børresen, T., 1999. The effect of straw management and reduced tillage on soil properties and
 445 crop yields of spring-sown cereals on two loam soils in Norway. *Soil & Tillage Research*, **51**,
 446 91-102.

447 Cayuela, M.L., Kuikman, P., Bakkers, R. & van Groenigen, J.W. 2013. Tracking C and N dynamics
 448 and stabilization in soil amended with wheat residue and its corresponding bioethanol by-
 449 product: a $^{13}\text{C}/^{15}\text{N}$ study. *Global Change Biology Bioenergy*, DOI: 10.1111/gcbb.12102.

450 Chen, H., Li, X., Hu, F. & Shi, W. 2013. Soil nitrous oxide emissions following crop residue
 451 addition: a meta-analysis. *Global Change Biology*, **19**, 2956-2964.

452 Chivenge, P.P., Murwira, H.K., Giller, K.E., Mapfumo, P. & Six, J. 2007. Long-term impact of
 453 reduced tillage and residue management on soil carbon stabilization: Implications for
 454 conservation agriculture on contrasting soils. *Soil & Tillage Research*, **94**, 328-337.

455 Cvetkov, M., Santavec, I., Kocjan Acko, D. & Tajnsek, A. 2010. Soil organic matter content
 456 according to different management system within long-term experiment. *Acta agriculturae*
 457 *Slovenica*, **95**, 79-88.

458 Cvetkov, M. & Tajnsek, A. 2009. Soil organic matter changes according to the application of
 459 organic and mineral fertilizers within long-term experiments. *Acta agriculturae Slovenica*, **93**,
 460 311-320.

461 De Neve, S. & Hofman, G. 2000. Influence of soil compaction on carbon and nitrogen
 462 mineralization of soil organic matter and crop residues. *Biology and Fertility of Soils*, **30**, 544-
 463 549.

464 European Commission. 2006. Thematic Strategy for Soil Protection. Commission of the European
 465 Communities, Brussels, Belgium, COM(2006) 231. Available at: eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2006:0231:FIN:EN:PDF;
 466 accessed
 467 12/16/2013.

468 Feller, C. & Beare, M.H. 1997. Physical control of soil organic matter dynamics in the tropics.
 469 *Geoderma*, **79**, 69-116.

470 Garcia-Ruiz, R. & Baggs, E.M. 2007. N₂O emission from soil following combined application of
 471 fertilizer-N and ground weed residues. *Plant and Soil*, **299**, 263-274.

472 Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mäder, P., Stolze, M.,
 473 Smith, P., El-Hage Scialabba, N. & Niggli, U. 2012. Enhanced top soil carbon stocks under
 474 organic farming. *Proceedings of the National Academy of Sciences*, **109**, 18226-18231.

475 Grignani, C., Zavattaro, L., Sacco, D. & Monaco, S. 2007. Production, nitrogen and carbon balance
 476 of maize-based forage systems. *European Journal of Agronomy*, **26**, 442-453.

477 Hege, U. & Offenberger, K. 2006. Effect of differentiated mineral fertilization and organic
 478 manuring on yield, product quality and N balances in the international permanent organic
 479 nitrogen experiment (IOSDV) Puch. *Archives of Agronomy and Soil Science*, **52**, 535-550.

480 Ingram, J.S.I. & Fernandes, E.C.M. 2001. Managing carbon sequestration in soils: concepts and
 481 terminology. *Agriculture, Ecosystems & Environment*, **87**, 111-117.

482 Janowiak, J. 1995. Influence of manure fertilization with straw addition and different nitrogen
 483 doses on properties of organic matter. *Zeszyty Problemowe postępow nauk rolniczych*, **421a**,
 484 145-150.

485 Jongman, R.H.G., Bunce, R.G.H., Metzger, M.J., Múcher, C.A., Howard, D.C. & Mateus, V.L. 2006.
 486 Objectives and applications of a statistical environmental stratification of Europe. *Landscape*
 487 *Ecology*, **21**, 409–419.

488 Körschens, M. 2006. The importance of long-term field experiments for soil science and
 489 environmental research – a review. *Plant, Soil and Environment*, **52**, 1-8.

490 Körschens, M., Weigel, A. & Schulz, E. 1998. Turnover of Soil Organic Matter (SOM) and Long-
 491 Term Balances – Tools for Evaluating Sustainable Productivity of Soils. *Zeitschrift für*
 492 *Pflanzenernährung und Bodenkunde*, **161**, 409-424.

493 Lajeunesse, M.J. 2011. On the meta-analysis of response ratios for studies with correlated and
 494 multi-group designs. *Ecology*, **92**, 2049-2055.

495 Lal, R. 2013. Intensive Agriculture and the Soil Carbon Pool. *Journal of Crop Improvement*, **27**,
 496 735-751.

497 Lal, R. 1997. Residue management, conservation tillage and soil restoration for mitigating
 498 greenhouse effect by CO₂-enrichment. *Soil & Tillage Research*, **43**, 81-107.

499 Leinweber, P. & Reuter, G. 1992. The influence of different fertilization practices on
 500 concentrations of organic carbon and total nitrogen in particle-size fractions during 34 years
 501 of a soil formation experiment in loamy marl. *Biology and Fertility of Soils*, **13**, 119-124.

502 Lemke, R.L., Van den Bygaart, A.J., Campbell, C.A., Lafond, G.P. & Grant, B. 2010. Crop residue
 503 removal and fertilizer N: Effects on soil organic carbon in a long-term crop rotation
 504 experiment on a Udic Boroll. *Agriculture, Ecosystems and Environment*, **135**, 42-51.

505 Liu, C., Lu, M., Cui, J., Li, B. & Fang, C. 2014. Effects of straw carbon input on carbon dynamics
 506 in agricultural soils: a meta-analysis. *Global Change Biology*, doi: 10.1111/gcb.12517.

507 Loveland, P. & Webb, J. 2003. Is there a critical level of organic matter in the agricultural soils of
 508 temperate regions: a review. *Soil & Tillage Research*, **70**, 1-18.

509 Lubet, E., Plénet, D. & Juste, C. 1993. Effet à long terme de la monoculture sur le rendement en
 510 grain du maïs (*Zea mays* L) en conditions non irriguées. *Agronomie*, **13**, 673-683.

511 Maiorana, M., Convertini, G. & Fornaro, F. 2004. Gestione del suolo nella omosuccessione di
 512 grano duro. *Informatore agrario*, **60**, 79-82.

513 Maiorana, M. 1998. Interramento dei residui colturali di frumento duro. *Informatore agrario*, **54**,
 514 41-45.

515 Marschner, P., Kandeler, E. & Marschner, B. 2003. Structure and function of the soil microbial
 516 community in a long-term fertilizer experiment. *Soil Biology & Biochemistry*, **35**, 453-461.

517 Meijide, A., Cárdenas, L.M., Sánchez-Martín, L. & Vallejo, A. 2010. Carbon dioxide and methane
 518 fluxes from a barley field amended with organic fertilizers under Mediterranean climatic
 519 conditions. *Plant and Soil*, **328**, 353-367.

520 Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., Múcher, C.A. & Watkins, J.W. 2005. A climatic
 521 stratification of the environment of Europe. *Global Ecology and Biogeography*, **14**, 549-563.

522 MLUV (Ministerium für Ländliche Entwicklung, Umwelt und Verbraucherschutz des Landes
 523 Brandenburg). 2009. Dauerfeldversuche in Brandenburg und Berlin - Beiträge für eine
 524 nachhaltige Landwirtschaftliche Bodennutzung. Available at:
 525 <http://lelf.brandenburg.de/sixcms/media.php/4055/Dauerfeldversuche%20f%C3%BCr%20nachhaltige%20Landwirtschaftliche%20Bodennutzung.pdf>; accessed at 11/6/2013.

527 Murphy, D.V., Stockdale, E.A., Poulton, P. R., Willison, T. W. & Goulding, K.W.T. 2007. Seasonal
 528 dynamics of carbon and nitrogen pools and fluxes under continuous arable and ley-arable
 529 rotations in a temperate environment. *European Journal of Soil Science*, **58**, 1410-1424.

530 Mutegei, J.K., Munkholm, L.J., Petersen, B.M., Hansen, E.M. & Petersen, S.O. 2010. Nitrous oxide
531 emissions and controls as influenced by tillage and crop residue management strategy. *Soil*
532 *Biology & Biochemistry*, **42**, 1701-1711.

533 Nedved, V., Balík, J., Cerný, J., Kulhánek, M. & Balíková, M. 2008. The changes of soil nitrogen and
534 carbon contents in a long-term field experiment under different systems of nitrogen
535 fertilization. *Plant, Soil and Environment*, **54**, 463-470.

536 Nicholson, F.A., Chambers, B.J., Mills, A.R. & Strachan, P.J. 1997. Effects of repeated straw
537 incorporation on crop fertilizer nitrogen requirements, soil mineral nitrogen and nitrate
538 leaching losses. *Soil Use and Management*, **13**, 136-142.

539 Nicolardot, B., Recous, S. & Mary, B. 2001. Simulation of C and N mineralisation during crop
540 residue decomposition: A simple dynamic model based on the C:N ratio of the residues. *Plant*
541 *and Soil*, **228**, 83-103.

542 Perucci, P., Bonciarelli, U., Santilocchi, R. & Bianchi, A.A. 1997. Effect of rotation, nitrogen
543 fertilization and management of crop residues on some chemical, microbiological and
544 biochemical properties of soil. *Biology and Fertility of Soils*, **24**, 311-316.

545 Petersen, S.O., Mutegei, J.K., Hansen, E.M. & Munkholm, L.J. 2011. Tillage effects on N₂O emissions
546 as influenced by a winter cover crop. *Soil Biology & Biochemistry*, **43**, 1509-1517.

547 Plénet, D., Lubet, E. & Juste, C. 1993. Évolution á long terme du statut carboné du sol en
548 monoculture non irriguée du maïs (*Zea mays* L). *Agronomie*, **13**, 685-698.

549 Poirier, V., Angers, D.A., Rochette, P. & Whalen, J.K. 2013. Initial soil organic carbon
550 concentration influences the short-term retention of crop-residue carbon in the fine fraction
551 of a heavy clay soil. *Biology and Fertility of Soils*, **49**, 527-535.

552 Powlson, D.S., Bhogal, A., Chambers, B.J., Coleman, K., Macdonald, A.J., Goulding, K.W.T. &
553 Whitmore, A.P. 2012. The potential to increase soil carbon stocks through reduced tillage or
554 organic material additions in England and Wales: A case study. *Agriculture, Ecosystems and*
555 *Environment*, **146**, 23-33.

556 Powlson, D.S., Glendining, M.J., Coleman, K. & Whitmore, A.P. 2011. Implications for Soil
 557 Properties of Removing Cereal Straw: Results from Long-Term Studies. *Agronomy Journal*,
 558 **103**, 279-287.

559 Powlson, D.S., Riche, A.B., Coleman, K., Glendining, M.J. & Whitmore, A.P. 2008. Carbon
 560 sequestration in European soils through straw incorporation: Limitations and alternatives.
 561 *Waste Management*, **28**, 741-746.

562 Recous, S., Robin, D., Darwis, D. & Mary, B. 1995. Soil inorganic N availability: Effect on maize
 563 residue decomposition. *Soil Biology and Biochemistry*, **27**, 1529–1538.

564 Rizhiya, E.Y., Boitsova, L.V., Buchkina, N.P. & Panova, G.G. 2011. The influence of crop residues
 565 with different C:N ratios on the N₂O emission from a loamy sand soddy-podzolic soil. *Eurasian*
 566 *Soil Science*, **44**, 1144-1151.

567 Rogasik, J., Schroetter, S., Schnug, E. & Kundler, P. 2001. Langzeiteffekte ackerbaulicher
 568 massnahmen auf die bodenfruchtbarkeit. *Archives of Agronomy and Soil Science*, **47**, 3-17.

569 Rohatgi, A. 2013. WebPlotDigitizer Version 2.6. Available at:
 570 <http://arohatgi.info/WebPlotDigitizer>; accessed at 12/11/2013.

571 Ruehlmann, J. & Körschens, M. 2009. Calculating the Effect of Soil Organic Matter Concentration
 572 on Soil Bulk Density. *Soil Science Society of America Journal*, **73**, 876-885.

573 Rühlmann, J., Körschens, M. & Graefe, J. 2006. A new approach to calculate the particle density of
 574 soils considering properties of the soil organic matter and the mineral matrix. *Geoderma*, **130**,
 575 272-283.

576 Rühlmann, J. 2006. The Box Plot Experiment in Grossbeeren after six rotations: Effect of
 577 fertilization on crop yield. *Archives of Agronomy and Soil Science*, **52**, 313-319.

578 Rühlmann, J. & Ruppel, S. 2005. Effects of organic amendments on soil carbon content and
 579 microbial biomass – results of the long-term box plot experiment in Grossbeeren. *Archives of*
 580 *Agronomy and Soil Science*, **51**, 163-170.

581 Sanz-Cobena, A., García-Marco, S., Quemada, M., Gabriel, J.L., Almendros, P. & Vallejo, A. 2014. Do
582 cover crops enhance N₂O, CO₂ or CH₄ emissions from soil in Mediterranean arable systems?
583 *Science of the Total Environment*, **466-467**, 164-174.

584 Shan, J. & Yan, X. 2013. Effects of crop residue returning on nitrous oxide emissions in
585 agricultural soils. *Atmospheric Environment*, **71**, 170-175.

586 Simon, T., Mikanova, O. & Cerhanova, D. 2013. Long-term effect of straw and farmyard manure
587 on soil organic matter in field experiment in the Czech Republic. *Archives of Agronomy and*
588 *Soil Science*, **59**, 1193-1205.

589 Smith, W.N., Grant, B.B., Campbell, C.A., McConkey, B.G., Desjardins, R.L., Kröbel, R., & Malhi, S.S.
590 2012. Crop residue removal effects on soil carbon: Measured and inter-model comparisons.
591 *Agriculture, Ecosystems and Environment*, **161**, 24-38.

592 Spiegel, H., Dersch, G. & Baumgarten, A. 2010a. Long term field experiments - a basis to evaluate
593 parameters of soil fertility. In: New Challenges in field crop production 2010, Proceedings of
594 Symposium (eds D. Kocjan Acko & B. Ceh), Slovensko agronomsko drustvo, Ljubljana,
595 Slovenia, pp.76-82.

596 Spiegel, H., Dersch, G., Baumgarten, A. & Hösch, J. 2010b. The International Organic Nitrogen
597 Long-term Fertilisation Experiment (IOSDV) at Vienna after 21 years. *Archives of Agronomy*
598 *and Soil Science*, **56**, 405-420.

599 Swan, J.B., Higgs R.L., Bailey T.B., Wollenhaupt N.C., Paulson W.H. & Peterson A.E. 1994. Surface
600 residue and in-row treatment on long-term no-tillage continuous corn. *Agronomy Journal*, **86**,
601 711-718.

602 Tajnsek, A., Cergan, Z. & Ceh, B. 2013. Results of the long-term field experiment IOSDV Rakican at
603 the beginning of the 21st century. *Archives of Agronomy and Soil Science*, **59**, 1109-1119.

604 Triberti, L., Nastri, A., Giordani, G., Comellini, F., Baldoni, G. & Toderi, G. 2008. Can mineral and
605 organic fertilization help sequester carbon dioxide in cropland? *European Journal of*
606 *Agronomy*, **29**, 13-20.

- Kismányoky, T. & Toth, Z. 2010. Effect of mineral and organic fertilization on soil fertility as well as on the biomass production and N utilization of winter wheat (*Triticum aestivum* L.) in a long-term cereal crop rotation experiment (IOSDV). *Archives of Agronomy and Soil Science*, **56**, 473-479.
- Lugato, E., Berti, A. & Giardini, L. 2006. Soil organic carbon (SOC) dynamics with and without residue incorporation in relation to different nitrogen fertilization rates. *Geoderma*, **135**, 315-321.
- Uhlen, G. 1991. Long-Term Effects of Fertilizers, Manure, Straw and Crop-Rotation on Total-N and Total-C in Soil. *Acta Agriculturae Scandinavica*, **41**, 119-127.
- Velthof, G.L., Kuikman, P.J. & Oenema, O. 2002. Nitrous oxide emission from soils amended with crop residues. *Nutrient Cycling in Agroecosystems*, **62**, 249-261.
- von Lützow M., Kögel- Knabner I., Ekschmitt K , Matzner E., Guggenberger G., Marschner B. & Flessa H., 2006. Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions - a review. *European Journal of Soil Science*, **57**, 426-445.
- Wilhelm, W.W., Johnson, J.M.F., Hatfield, J.L., Voorhees, W.B. & Linden, D.R. 2004. Crop and soil productivity response to corn residue removal. *Agronomy Journal*, **96**, 1-17.
- Zavattaro, L., Monaco, S., Sacco, D. & Grignani, C. 2012. Options to reduce N loss from Maize in intensive cropping systems in Northern Italy. *Agriculture, Ecosystems and Environment*, **147**, 24-35.

628 **Figures**

629 **Figure 1** Map of the experiment locations and their distribution across the aggregated
630 environmental zones (Nemoral, Atlantic, Continental, Mediterranean).

631 **Figure 2** Response ratios (RRs) in A,C,E) SOC concentrations, and B,D,F) SOC stocks across A,B)
632 environmental zones (ENZs), C,D) clay contents (%), and E,F) experiment durations (years). The
633 left vertical line of the box represents the first quartile, median is shown as a thick line, and the
634 right vertical line represents the third quartile. Horizontal bars show the minimum and
635 maximum values. The (°) and (*) denote outliers. The figure is based on the original data on
636 response ratios, without any weighting procedure. The numbers of RR (and experiments) are
637 presented for each category along the y-axis. Different letters indicate significant differences
638 according to Tukey's as a Post Hoc test ($p < 0.05$).

639 **Figure 3** Correlation between RR for SOC concentration and crop yields A) across the sites, B)
640 across the aggregated environmental zones, C) across the clay contents, and D) across the
641 experiment durations. The figure is based on the original data on response ratios, without any
642 weighting procedure.

643 **Tables**

644 **Table 1** Description of sites included in the analysis.

645 **Table 2** Aggregated variables and specific levels of each variable.

646 **Table 3** Significant results of multiple regressions.

647 **Table 4** Mean response ratios of GHG emissions in crop residue incorporation management
648 practice compared to crop residue removal management practice in different environmental
649 zones (ENZ), clay contents (%), and experiment durations (years). The values have been
650 calculated from average data from each experiment and were weighted based on the amount of
651 response ratios calculated into the average.

Table 1 Summary description of sites included in the analysis.

Experiment Nr	Experiment	Country	Location	Environmental zone ^a	Start year	Soil texture	References
<i>Field studies</i>							
1	Ås	Norway	59°39'N 10°47'E	NEM	1953	clay loam	Uhlen, 1991
2	Øsaker	Norway	59°23'N 11°02'E	NEM	1963	silty clay loam	Uhlen, 1991, Børresen, 1999
3	Ultuna	Sweden	59° 00'N 17°00'E	NEM	1956	clay loam	Börjesson et al., 2012
4	Foulum	Denmark	56°30'N 09°34'E	ATN	1997	sandy loam	Mutegi et al., 2010; Petersen et al., 2011
5	Studsgaard	Denmark	56°05'N 08°54'E	ATN	1969	loamy sand	Powlson et al., 2011
6	Askov	Denmark	55°28'N 09°07'E	ATN	1894	sandy loam	Powlson et al., 2011
7	Rønhave	Denmark	54°54'N 09°47'E	ATN	1969	sandy loam	Powlson et al., 2011
8	Edinburgh	UK	55°57'N 03°11'W	ATN	1995	clay loam	Ball et al., 1990
9	Morley	UK	52°34'N 01°06'W	ATN	1984	sandy loam	Nicholson et al., 1997; Powlson et al., 2011
10	Gleadthorpe	UK	53°13'N 01°05'W	ATC	1984	loamy sand	Nicholson et al., 1997
11	Woburn	UK	51°59'N 00°37'W	ATC	1938	sandy loam	Murphy et al., 2007; Powlson et al., 2011
12	Rothamsted	UK	51° 48'N 00°21'W	ATC	1852	clay	Powlson et al., 2011
13	Wye Estate	UK	51°10'N 00°56'E	ATC	1999	silty loam	Baggs et al., 2003
14	Cologne	Germany	50°56'N 06°57'E	ATC	1969	silt	Marschner et al., 2003
15	Gembloux	Belgium	50°33'N 04°41'E	ATC	1959	silty loam	Powlson et al., 2011
16	Wierzchucinek	Poland	53°15'N 17°47'E	CON	1979	sandy loam	Janowiak, 1995
17	Rostock	Germany	54°05'N 12°08'E	CON	1954	loam	Leinweber & Reuter, 1992
18	Müncheberg	Germany	52°30'N 14°08'E	CON	1962	silty loam	Rogasik et al., 2001
19	Grossbeeren 1	Germany	52°21'N 13°18'E	CON	1972	loamy sand	Rühlmann & Ruppel, 2005; Rühlmann, 2006; MLUV, 2009
20	Grossbeeren 2	Germany	52°21'N 13°18'E	CON	1972	sandy loam	Rühlmann & Ruppel, 2005; Rühlmann, 2006; MLUV, 2009
21	Grossbeeren 3	Germany	52°21'N 13°18'E	CON	1972	silt	Rühlmann & Ruppel, 2005; Rühlmann, 2006; MLUV, 2009
22	Braunschweig	Germany	52°18'N 10°27'E	CON	1952	silty loam	Rogasik et al., 2001
23	Spröda	Germany	51°32'N 12°25'E	CON	1966	sandy loam	Albert & Grunert, 2013
24	Methau	Germany	51°04'N 12°51'E	CON	1966	silty loam	Albert & Grunert, 2013
25	Puch	Germany	48°11'N 11°13'E	CON	1984	silty loam	Hege & Offenberger, 2006
26	Suchdol	Czech Republic	49° 57'N 15°09'E	CON	1997	loam	Nedved et al., 2008

27	Lukavec	Czech Republic	49°33'N 14°59'E	CON	1997	sandy loam	Nedved et al., 2008
28	Alpenvorland	Austria	48°07'N 15°08'E	CON	1986	silty loam	Spiegel et al., 2010a
29	Marchfeld	Austria	48°13'N 16°36'E	PAN	1982	sandy loam	Spiegel et al., 2010a
30	Vienna	Austria	48°11'N 16°44'E	PAN	1986	loamy sand	Spiegel et al., 2010b
31	Keszthely	Hungary	46°44'N 17°13'E	PAN	1960	sandy loam	Kismanyoky & Toth, 2013
32	Trutnov	Czech Republic	50°33'N 15° 53'E	ALS	1966	sandy loam	Simon et al., 2013
33	Rakican	Slovenia	46°38'N 16°11'E	ALS	1993	loamy sand	Cvetkov & Tajnsek 2009; Cvetkov et al., 2010; Tajnsek et al., 2013
34	Jable	Slovenia	46°08'N 14°34'E	ALS	1993	silty loam	Cvetkov & Tajnsek 2009
35	Grignon	France	45°39'N 06°22'E	ALS	1963	loam	Powlson et al., 2011
36	Doazit	France	43°41'N 00°38'W	LUS	1967	loamy sand	Plénet et al., 1993
37	Serreslous	France	43°40'N 00°40'W	LUS	1967	silty loam	Plénet et al., 1993; Lubet et al., 1993
38	Tetto Frati	Italy	44°53'N 07°41'E	MDM	1992	loam	Grignani et al., 2007; Bertora et al., 2009; Zavattaro et al., 2012
39	Padova	Italy	45°21'N 11°58'E	MDN	1966	clay loam	Lugato et al., 2006
40	Papiano	Italy	42°57'N 12°20'E	MDN	1971	loam	Bianchi et al., 1994; Perucci et al., 1997
41	Foggia 1	Italy	41°27'N 15°32'E	MDN	1977	clay	Maiorana, 1998; Maiorana et al. 2004
42	Foggia 2	Italy	41°27'N 15°32'E	MDN	1990	clay	Maiorana, 1998; Maiorana et al. 2004
43	Almacelles 1	Spain	41°43'N 00°26'E	MDS	2010	clay loam	Biau et al., 2013
44	Almacelles 2	Spain	41°43'N 00°26'E	MDS	2010	loam	Biau et al., 2013
45	El Encín	Spain	40°32'N 03°17'W	MDS	2010	clay loam	Meijide et al., 2010; Abalos et al., 2013
46	La Chimenea	Spain	40°03'N 03°31'W	MDS	2009	silty clay loam	Sanz-Cobena et al., 2014
<i>Laboratory studies</i>							
47	Flevopolder	The Netherlands	52°30'N 05°28'E	ATC	1999	clay	Velthof et al., 2002
48	Wageningen	The Netherlands	51°58'N 05°39'E	ATC	1999	sand	Velthof et al., 2002
49	Wijnandsrade	The Netherlands	50°54'N 05°52'E	ATC	N/A	silty loam	Cayuela et al., 2013
50	Wye Estate	UK	51°10'N 00°56'E	ATC	1999	silty loam	Garcia-Ruiz & Baggs, 2007

^aEnvironmental zone assigned according to Metzger et al. (2005): NEM, Nemoral; ATN, Atlantic North; ATC, Atlantic Central; CON, Continental; PAN, Pannonian; ALS, Alpine South; LUS, Lusitanian; MDM, Mediterranean Mountains; MDN, Mediterranean North; MDS, Mediterranean South.

Table 2 Aggregated variables and specific levels of each variable.

Variable	Specific levels			
ENZ ^a	Nemoral (NEM)	Atlantic (ATN, ATC, LUS)	Continental (CON, PAN, ALS)	Mediterranean (MDM, MDN, MDS)
Clay %	<18 %	18-35 %	>35%	
Experiment duration ^b	<5 years	5-10 years	11-20 years	>20 years

^aEnvironmental zone assigned according to Metzger et al. (2005): NEM, Nemoral; ATN, Atlantic North; ATC, Atlantic Central; CON, Continental; PAN, Pannonian; ALS, Alpine South; LUS, Lusitanian; MDM, Mediterranean Mountains; MDN, Mediterranean North; MDS, Mediterranean South.

^b Experiment duration: years between the beginning of the experiment and the measurement.

Table 3 Significant results of multiple regressions.

<i>LOG RR of SOC concentration</i>					
	R ²	F	P	n	
Model	0.140	34.385	<0.0001	213	
Variables	Coefficient	SE ^a	95% CI ^b	T	P
Intercept	0.008	0.004	0.001-0.016	2.125	0.035
Duration	0.001	0.0002	0.0006-0.0012	5.864	<0.0001
<i>LOG RR of SOC stock</i>					
	R ²	F	P	n	
Model	0.218	33.405	<0.0001	243	
Variables	Coefficient	SE	95% CI	T	P
Intercept	0.046	0.005	0.035-0.057	8.458	<0.0001
Clay content	-0.002	0.0002	-0.002-(-)0.001	-6.61	<0.0001
Duration	0.001	0.0001	0.0005-0.001	5.67	<0.0001
<i>LOG RR of CO₂ emissions</i>					
	R ²	F	P	n	
Model	0.983	1297.063	<0.0001	41	
Variables	Coefficient	SE	95% CI	T	P
Intercept	0.494	0.012	0.469-0.159	40.608	<0.0001
Clay content	-0.018	0.001	-0.019-(-)0.017	-36.015	<0.0001

LOG RR of N₂O emissions

	R ²	F	P	n	
Model	0.752	44.845	<0.0001	37	
Variables	Coefficient	SE	95% CI	t	P
Intercept	0.5587	0.265	0.048-1.126	2.212	0.034
Clay content	0.098	0.017	0.068-0.133	5.721	<0.0001
Temperature	-0.185	0.052	-0.289-(-)0.080	-3.579	0.001

^aSE, standard error

^bCI, confidence interval

Table 4 Mean response ratios of GHG emissions in crop residue incorporation management practices compared to crop residue removal management practices in different aggregated environmental zones (ENZs), clay contents (%), and experiment durations (years). The values have been calculated from average data from each experiment and were weighted based on the amount of response ratios calculated into the average. Different letters indicate significant differences according to Tukey's as a Post Hoc test ($p < 0.05$).

		Cereal				Vegetative material			
		CO ₂				CO ₂			
		Mean	SD ^a	n exp ^b	n RR ^c	Mean	SD	n exp	n RR
Overall	Field	1.0a	0.08	3	17	1.7a	0.50	2	7
	Laboratory	2.4b	0.46	3	15	9.2b	3.9	3	50
<i>ENZ</i>									
Atlantic	Field	1.0	0.00	1	4	2.1	0.00	1	4
	Laboratory	2.4	0.46	3	15	9.2	3.9	3	50
Mediterranean	Field	1.0	0.09	2	13	1.1	0.00	1	3
	Laboratory	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
<i>Clay %</i>									
<18 %	Field	1.0	0.00	1	4	2.1	0.00	1	4
	Laboratory	2.4	0.46	3	15	9.2	3.9	3	50
18-35 %	Field	1.0	0.09	2	13	1.1	0.00	1	3
	Laboratory	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
<i>Duration</i>									
< 5 years	Field	1.0	0.08	3	17	1.7	0.50	2	7
	Laboratory	2.4	0.46	3	15	9.2	3.9	3	50
		Cereal				Vegetative material			

		N ₂ O				N ₂ O			
		Mean	SD	n exp	n RR	Mean	SD	n exp	n RR
Overall	Field	3.7a	3.60	4	30	1.9a	0.95	2	7
	Laboratory	2.3a	2.30	3	15	21.4b	20.4	3	50
<i>ENZ</i>									
Atlantic	Field	1.4	0.50	2	20	2.7	0.00	1	4
	Laboratory	2.3	2.30	3	15	21.4	20.4	3	50
Mediterranean	Field	8.4	2.34	2	10	0.9	0.00	1	3
	Laboratory	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
<i>Clay %</i>									
<18%	Field	1.4	0.50	2	20	2.7	0.00	1	4
	Laboratory	2.3	2.30	3	15	21.4	20.4	3	50
18-35%	Field	8.4	2.34	2	10	0.9	0.00	1	3
	Laboratory	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
<i>Duration</i>									
<5 years	Field	5.5	3.67	3	18	1.9	0.95	2	7
	Laboratory	2.3	2.30	3	15	21.4	20.4	3	50
11-20 years	Field	1.0	0.00	1	12	N/A	N/A	N/A	N/A
	Laboratory	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

^aSD, standard deviation.

^bn exp, number of experiments.

^cn RR, number of response ratios; RR, CO₂ or N₂O emissions in crop residue incorporation treatment/CO₂ or N₂O emissions in crop residue removal treatment.

N/A, not available.

Figure 1.

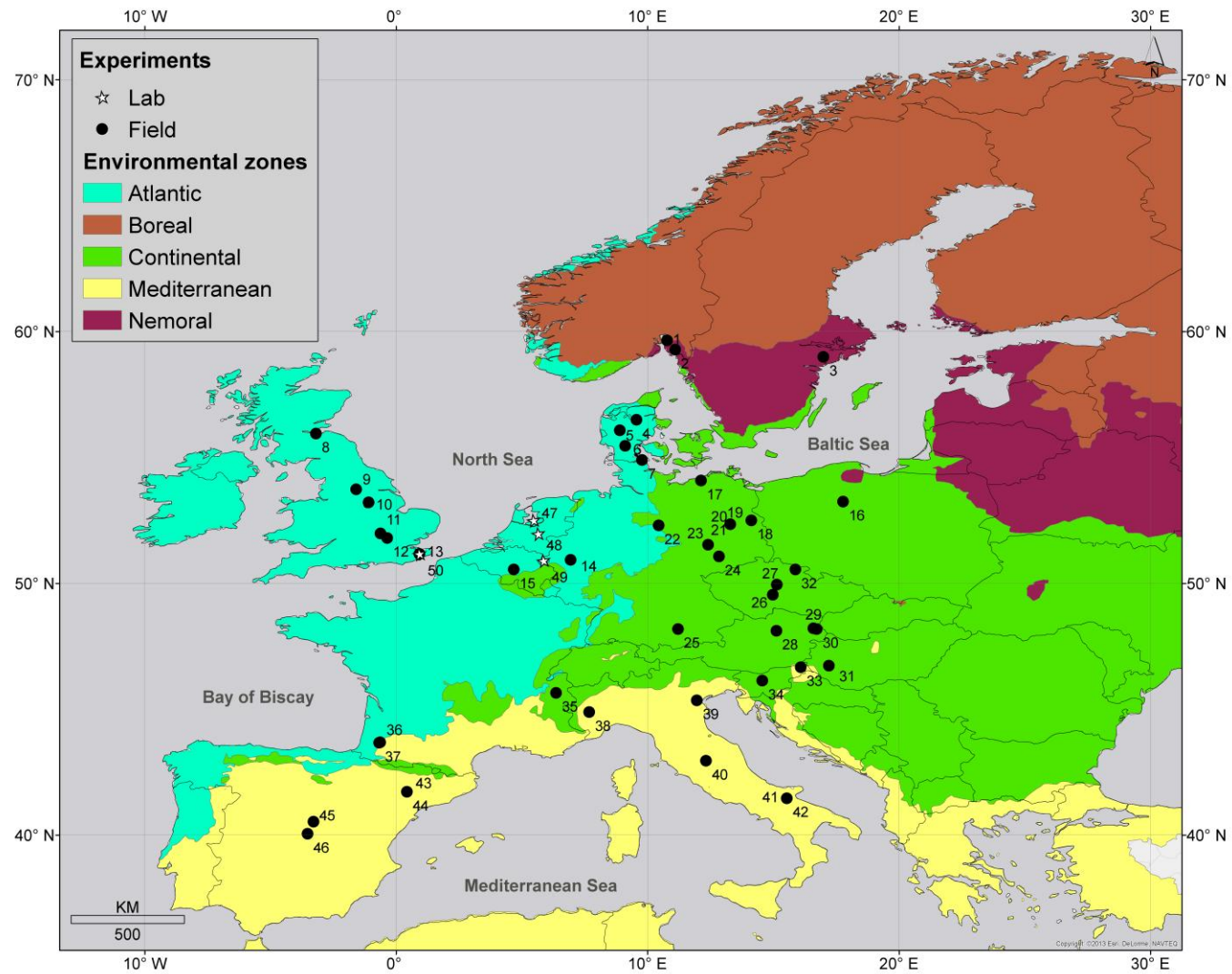


Figure 2.

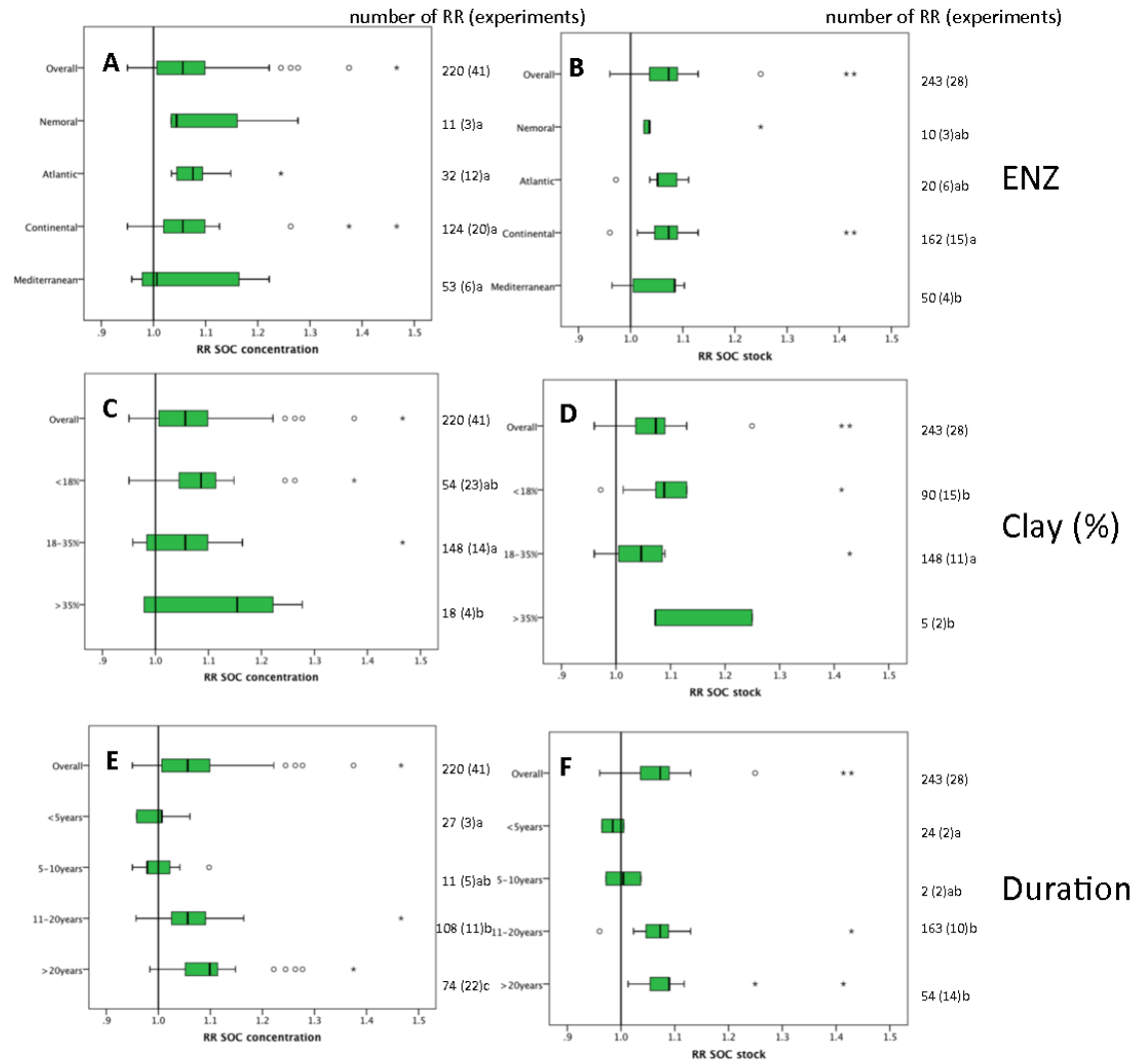


Figure 3

